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TECHNIQUES

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Advances in low energy neutral atom imaging techniques

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ABSTRACT

Recently proposed low energy neutral atom (LENA) imaging techniques use a collisional process to convert the low energy neutrals into ions before detection. At low energies, collisional processes limit the angular resolution and conversion efficiencies of these devices. However, if the intense ultraviolet light background can be suppressed, direct LENA detection is possible. We present results from a series of experiments designed to develop a novel filtering structure based on free-standing transmission gratings. If the grating period is sufficiently small, free standing transmission gratings can be employed to substantially polarize ultraviolet (UV) light in the wavelength range 300 Å to 1500 Å. If a second grating is placed behind the first grating with its axis of polarization oriented at a right angle to the first's, a substantial attenuation of UV radiation is achievable. The neutrals will pass through the remaining open area of two gratings and be detected without UV background complications. We have obtained nominal 2000 Å period (1000 Å bars with 1000 Å slots) free standing, gold transmission gratings and measured their UV and atomic transmission characteristics. The geometric factor of a LENA imager based on this technology is comparable to that of other proposed LENA imagers. In addition, this type of imager does not distort the neutral trajectories, allowing for high angular resolution.

2. INTRODUCTION

The potential for low energy neutral atom (LENA) imaging to greatly increase our understanding of the global morphology and dynamics of the terrestrial magnetosphere is becoming widely accepted in the space physics community.^{1,2,3,4} However, the technical challenges involved in manufacturing an effective LENA imager are substantial. The two biggest obstacles are the expected very low LENA fluxes and the intense ultraviolet (UV) background.⁵ Although indirect methods to detect LENAs by removing them from the UV environment with a moderate loss of imaging resolution have been proposed,⁶ a LENA imager that effectively blocks the UV background and permits direct detection of 100 eV to 10,000 eV LENAs will be capable of producing images with both high temporal and high spatial resolution. The significance of detecting 100 eV neutral hydrogen atoms is demonstrated in Figure 1. If one assumes an optically thin medium (low neutral and ion densities), and initially cold neutrals, the neutral flux as a function of energy, F , is given by the expression:

$$F(F)dF \approx n_0 F \sigma_{cx}(F) I_i(F) dF \quad (1)$$

where $I_i(F)$ is the ion energy distribution in the plasma, n_0 is the neutral density, and σ_{cx} is the energy dependent charge exchange cross section for the reaction,⁷



This second layer becomes the support structure after an ultraviolet lithography and gold electroplating step. The grating substrate is then etched off, leaving a free standing gold grating and support structure. The support structure typically has a transparency between thirty and forty percent. Our particular grating structure has a 2200 Å period transmission grating, consisting of 1500 Å wide bars and 700 Å wide spaces, and a support structure transparency of 34%. The transmission grating bars are 5110 Å deep. These characteristics were determined with a scanning electron microscope (SEM). Based on these grating characteristics, we expected an atomic transmission of 11.3%.

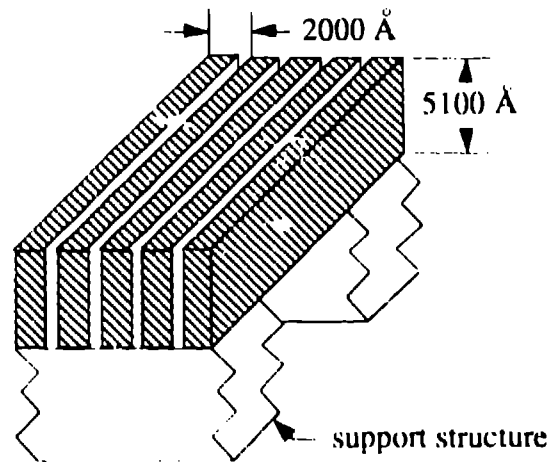


Figure 2. Schematic of the free standing gold grating structure.

To measure the atomic transmission of the grating, we placed the grating in a spatially uniform 10 keV proton beam. As shown in Figure 3, a microchannel plate (MCP) imaging system, consisting of three stacked MCPs and a position-sensitive resistive anode, was placed behind the grating to obtain a proton illuminated image of the grating (Fig. 4). Open holes were left in the grating holder and the atomic flux through the grating was compared to the unimpeded flux. Figure 4 clearly shows that the atomic transmission was not uniform across the grating structure. Few atoms appear to be able to pass through the center or the lower left corner of the grating. For the regions where atoms could pass through, the measured atomic transmission was 5.4%.

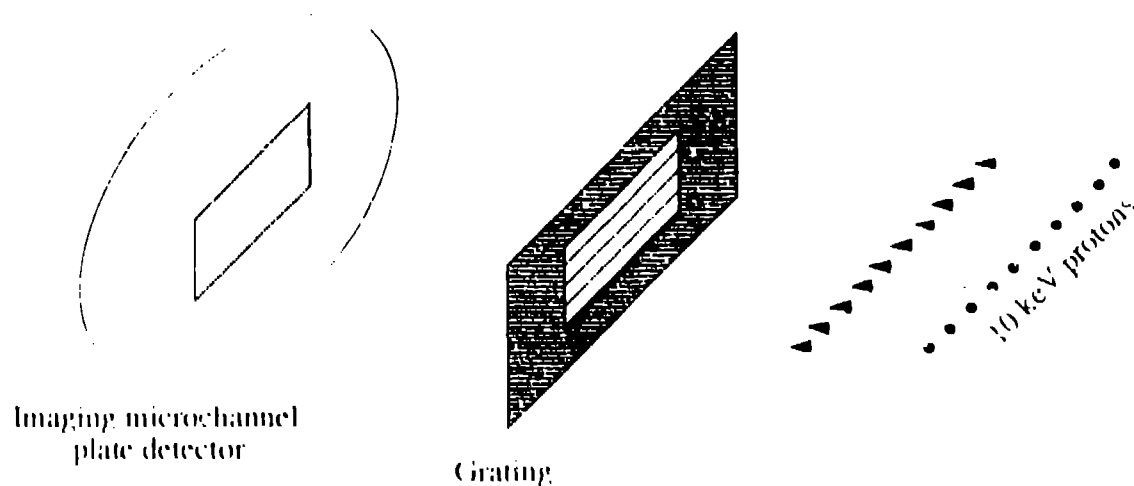


Figure 3. Schematic of the grating imaging process.

Figure 1 shows the expected neutral flux ($\text{cm}^2 \text{ sr s eV}^{-1}$) versus energy from a plasma with a Maxwellian ion distribution corresponding to a temperature of 3 keV, conditions similar to those observed in the Earth's plasma sheet. These substantial few 100's of eV hydrogen LENA fluxes cannot be observed by LENA imagers that rely on collisional processes to separate the neutrals from the ambient UV.

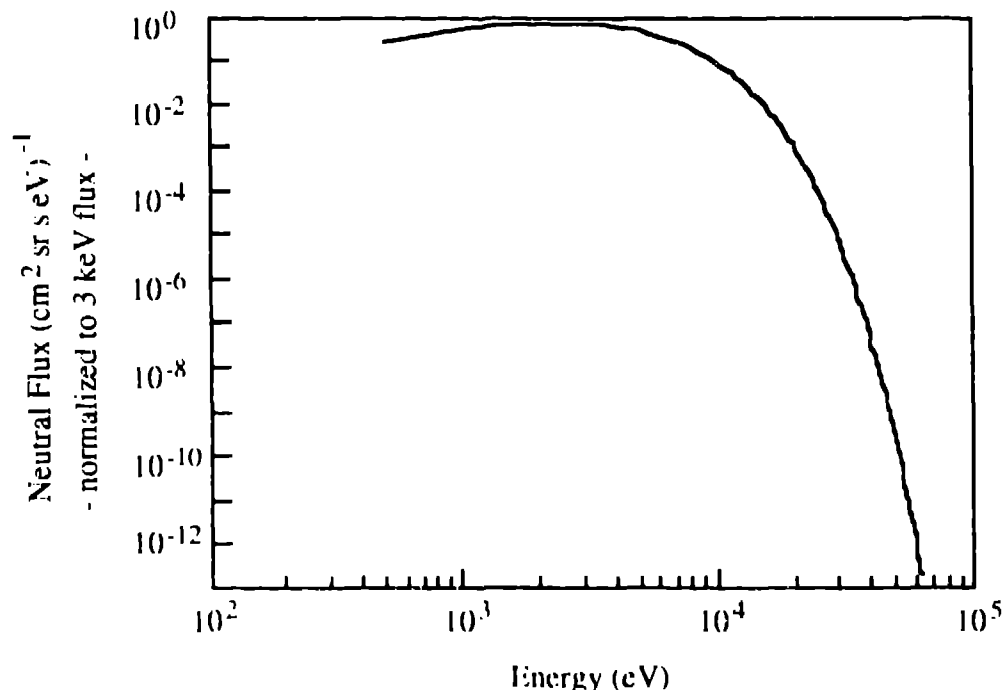


Figure 1. Neutral flux from an optically thin, $T = 3 \text{ keV}$ plasma as a function of neutral energy, normalized to the 3 keV neutral flux.

To remove the UV from the LENA flux, instead of removing the LENAs from the UV flux, we propose to polarize the UV radiation with a submicron, conductive transmission grating and then use a second grating oriented with its axis polarization perpendicular to the first, to effectively eliminate the UV. This approach, first suggested by Grunman,⁸ continues earlier work to suppress UV using diffraction filtering by submicron holes. A significant fraction of the final surface area will remain completely open, allowing LENAs to pass through unimpeded. In fact, preliminary measurements indicate a net open area for the grating pair of 5% is attainable.

We have obtained one of these transmission gratings and have measured its atomic and UV transmission properties. We have also modeled the UV transmission of the grating numerically using a complete vector simulation code.⁹ In this paper we present our preliminary particle and UV transmission measurements and compare them, respectively, to the measured bar and slits dimensions and the numerical simulation. We then describe the specifications, including geometric factor, of a grating based LENA imager.

3. PARTICLE MEASUREMENTS

A complete grating consists of a support structure and the actual transmission grating (Fig. 2). The transmission grating is formed first using a holographic lithography technique developed for the manufacture of gratings for the Advanced X-ray Astrophysics Facility (AXAF) satellite.¹⁰ After the grating is formed on a solid substrate, an additional photoresist layer is then spun over its upper surface.

After the atomic transmission image was obtained, the grating was examined under a high power microscope. A thin, shiny film was visible on the grating surface and after the UV transmission measurements, we returned the grating to the Massachusetts Institute of Technology Submicron Structures Laboratory where it was manufactured. Subsequent SEM examination confirmed the presence of an unknown layer of contamination on the grating surface.¹¹ We are currently in the process of obtaining a uniformly transmissive grating to continue these measurements.

The one dimensional angular resolution of the grating was determined by rotating the grating in the beam and agreed with the calculated value of 8° based on the depth-to-width SEM measurement of the slits.

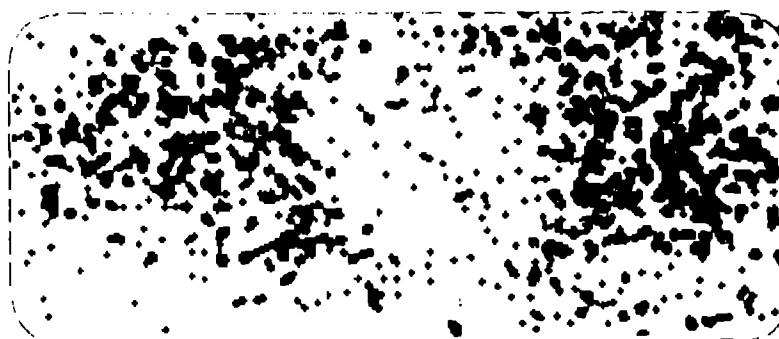


Figure 4. Proton illuminated image of the transmission grating showing a vaguely circular occlusion and poor transmission due to an unknown contamination layer.

4. ULTRAVIOLET MEASUREMENTS

The ultraviolet transmission properties of the grating were measured using a deuterium lamp continuum source over the wavelength range 150 to 190 nm (Fig. 5). To compensate for the limited dynamic range of the microchannel plate detector, we placed a number of calibrated filters between the source and the detector. With the filters we were able to cover 12 orders of magnitude of UV intensity for comparison with the gratings. The measured UV transmission of the grating was $(4 \pm 1) \times 10^{-9}$. Using the measured optical properties of gold over the same wavelength range,¹² the numerical simulation predicted a UV transmission of 4.4×10^{-9} (Fig. 6), which closely agrees with our empirical results. If the grating only functioned as a polarizer an attenuation of 5.4×10^{-2} ($34 \times (700/2200) \times 0.5$) would be intuitively expected. But from the viewpoint of the UV radiation, the grating is actually a long conductive slit; thus the grating also functions as an unmatched waveguide. This additional waveguide effect serves to attenuate the UV flux even further, without affecting the atomic transmission. Although we are not yet able to determine the degree of polarization of the UV radiation that exits the grating, the numerical simulation predicts a polarization approaching 98% for our grating. It should be noted that wire grids have been used as polarizers for many years with excellent results.^{13,14}

The E_{UV} ($\lambda = 121$ nm) intensity attenuation required for an effective low energy neutral imager is on the order of 10^{10} .¹⁵ Extrapolation of the simulation results for the single grating to two perpendicularly oriented 2200 Å period gratings with 700 Å slits, yields a net attenuation of E_{UV} of approximately 10^7 for initially unpolarized E_{UV} radiation, assuming a negligible phase shift of each polarization component. Including the 1% sensitivity of MCPs to E_{UV} ,¹⁵ an attenuation of 10^9 appears achievable with the current generation of gratings. Gratings with 1000 Å periods, which are under development,¹¹ should easily reach the 10^{10} attenuation goal. The simulation does not calculate the transmission through both gratings simultaneously and the possible effects of phase shifts of the transmitted polarization on the net attenuation are still being examined. The possible effects of mechanical imperfections in the gratings on the total attenuation are also being investigated.

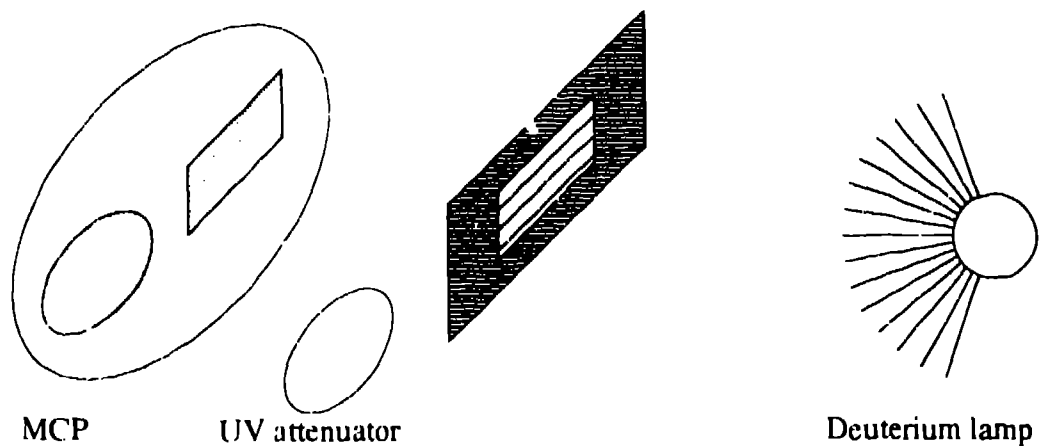


Figure 5. Schematic of the UV transmission apparatus.

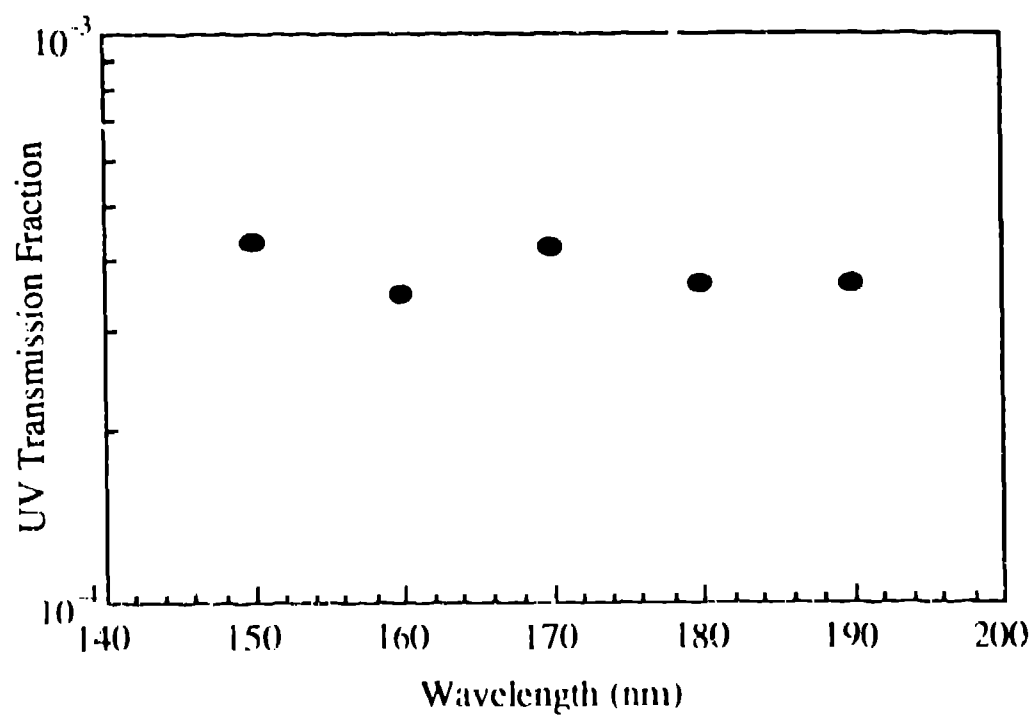


Figure 6. Transmission versus wavelength results from the numerical simulation for a 2200 Å period grating with 700 Å wide slits.

5. GRATING BASED NEUTRAL IMAGER SPECIFICATIONS

Assuming that sufficiently large gratings can be manufactured, an extraordinarily simple LENA imager can be constructed. All that is required is a charged particle rejecting collimator, two transmission gratings, and a microchannel plate stack with a position sensitive anode (Fig. 7). As noted previously, each

slot has a one dimensional angular resolution of 8° . The intrinsic azimuthal and polar resolution of the instrument is governed by the $8^\circ \times 8^\circ$ resolution of each open region of the transmission grating pair. The collimator can serve the dual purpose of rejecting charged particles, by the application of voltages across each collimator plates, and increasing the azimuthal resolution.¹⁶ Because this type of LENA imager has no energy resolution and incorporates thousands of individual pixels (the open areas remaining when the gratings are oriented perpendicularly to each other), the geometric factor (G), [$\text{cm}^2 \text{ sr eV/eV}$], calculation requires a slight modification:

$$G = G_{\text{pixel}} \cdot \text{number of pixels}$$

$$G_{\text{pixel}} = 2a\epsilon^2 \frac{\Delta E}{E} \Delta\alpha = 2a\epsilon^2 \Delta\alpha s \quad (2)$$

$$\text{number of pixels} = \frac{A}{p^2},$$

where a is the area of each pixel, $\Delta\alpha$ is the solid angle accepted by each pixel, A is the total area of grating, p is the period of the two *identical* transmission gratings, and ϵ is the transmission of the support mesh. The total counts, C , recorded by the detector are given by:

$$C = G \cdot \int F\eta dE, \quad (3)$$

where η is the detector efficiency and F is the neutral flux in [$\text{cm}^2 \text{ s sr eV}$] $^{-1}$. Based on a collimator with a 4° azimuthal acceptance, the calculated 8° polar acceptance of two gratings, and the measured aperture area of $4.9 \times 10^{-15} \text{ m}^2$:

$$G = 4A \sin(8^\circ) \left(\frac{4\pi}{180} \right) \cdot \left(a\epsilon^2 / p^2 \right) = 0.0005 A. \quad (4)$$

Note that the term,

$$\sqrt{a\epsilon^2 / p^2},$$

is also the measured particle transmission of a single grating (fraction of open area times the support structure transparency). Although the individual gratings, as currently manufactured, are not very large, we anticipate being able to group enough gratings together to create an aperture area of 100 cm^2 . The resulting geometric factor is 0.05. Not only is the geometric factor of a grating based LENA imager comparable to other proposed LENA imagers,¹⁶ the total counts available for imaging are a function of the *integrated* neutral flux from less than 100 eV to 10's of keV. The count rate of a polarizing grating LENA imager will therefore be many times larger than other proposed LENA imagers.³ In effect, the grating-based imager is a pinhole camera and thus no additional hardware is needed to ascertain the trajectory of the incident LENA. The output of the imaging MCP detector can be directly converted into an useful image. Because of its simple design and compact size, the total mass and power requirements of a grating-based imager are also a fraction of other LENA imager concepts.

The inability of this type of imager to obtain neutral images for different energy bands, a deficiency which could seriously hamper analysis of the images, can be corrected with some additional techniques already proposed for neutral imaging.¹⁶ A thin carbon foil could be placed in front of the MCP detector as shown in figure 8. Electrons produced at the foil surface could be used as start pulses and the MCP output as a stop pulse. Across many of the energy ranges and regions of interest, magnetospheric neutrals are predominantly H^0 ^{17,18} and a simple time of flight circuit could be used to gate the MCP output into energy bands. Because the UV flux has already been reduced by a factor of 10^8 , start pulse

production due to UV photons will be insignificant.⁵ For LENAs with energies above 5 keV the loss of angular resolution resulting from scattering in the foil will be negligible, but for LENAs below 1 keV the loss of angular resolution will be substantial.¹⁶

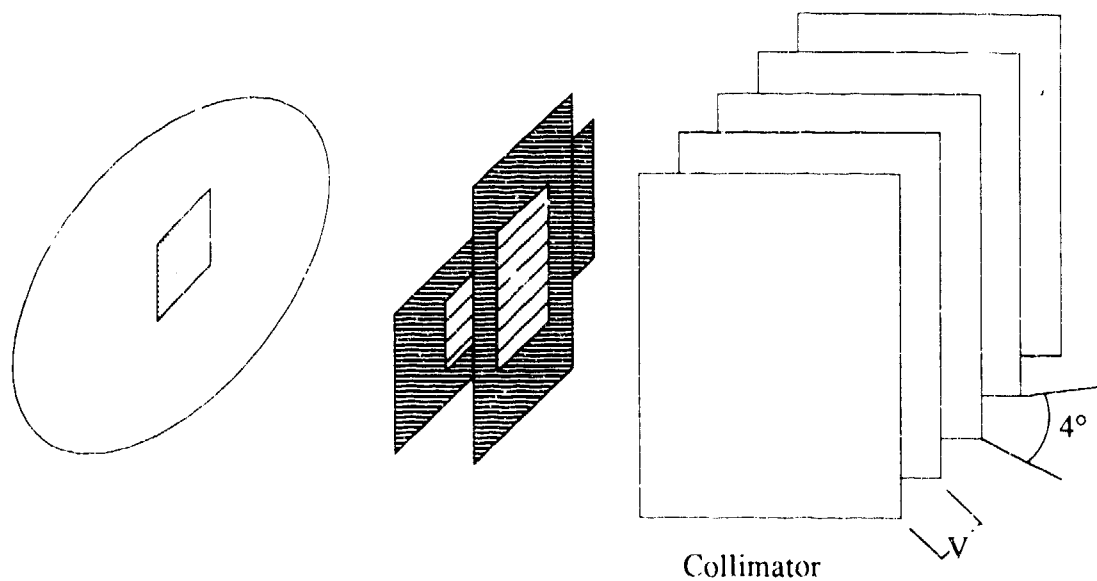


Figure 7. Grating based LENA imager including a collimator, two crossed gratings, and an imaging MCP detector.

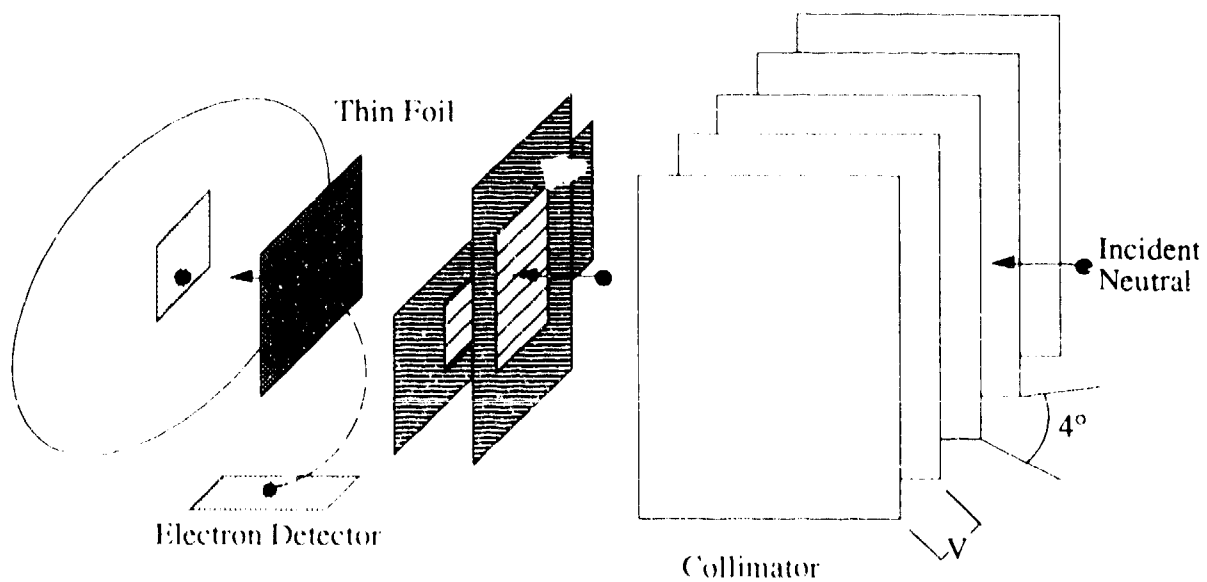


Figure 8. Same grating based LENA imager with thin foil added to generate start pulse for energy analysis.

6. DISCUSSION

Our preliminary measurements indicate that a grating-based LENA imager utilizing current technology is feasible. Because of its simple and compact design, a grating-based LENA imager has significant advantages over other proposed LENA imagers. The addition of a thin foil for energy information can also provide coincidence measurements. This additional information will be especially useful for eliminating the UV photons events resulting from the use of a grating pair with UV attenuation less than 10^{10} . We intend to continue our atomic and UV transmission studies of these gratings and assist the M.I.T. Submicron Structures Laboratory in the production of uniformly transmissive gratings. We are also assembling the necessary equipment for polarization and transmission studies using monochromatic UV radiation.

7. ACKNOWLEDGMENTS

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